Identification of algorithmic principles in intermediate vision using two-photon microscopy and evolving visual stimuli

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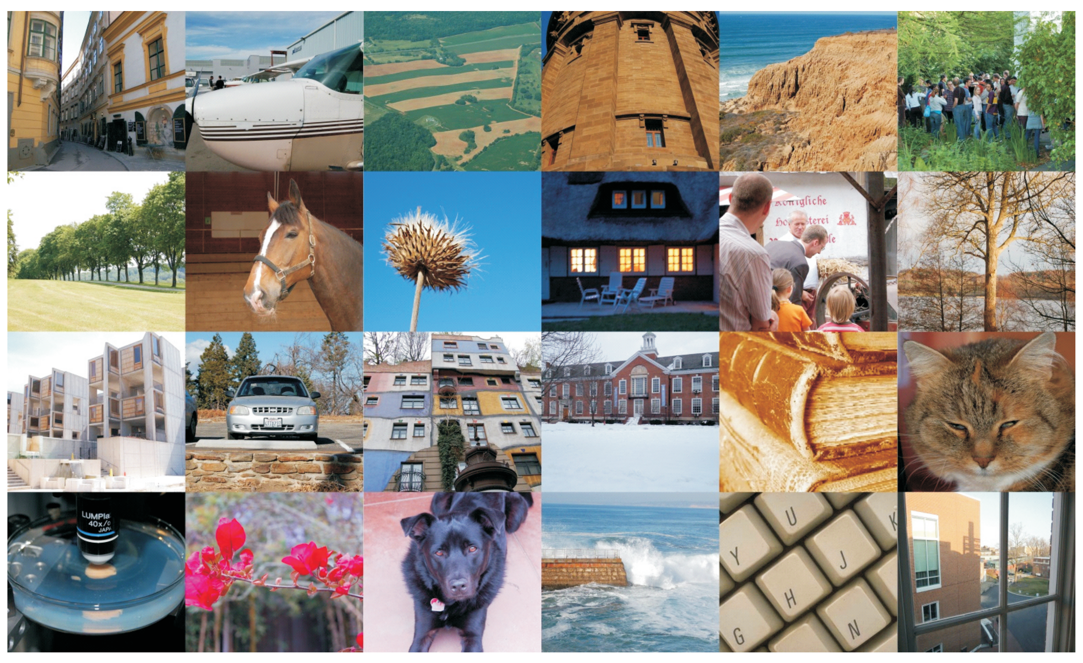
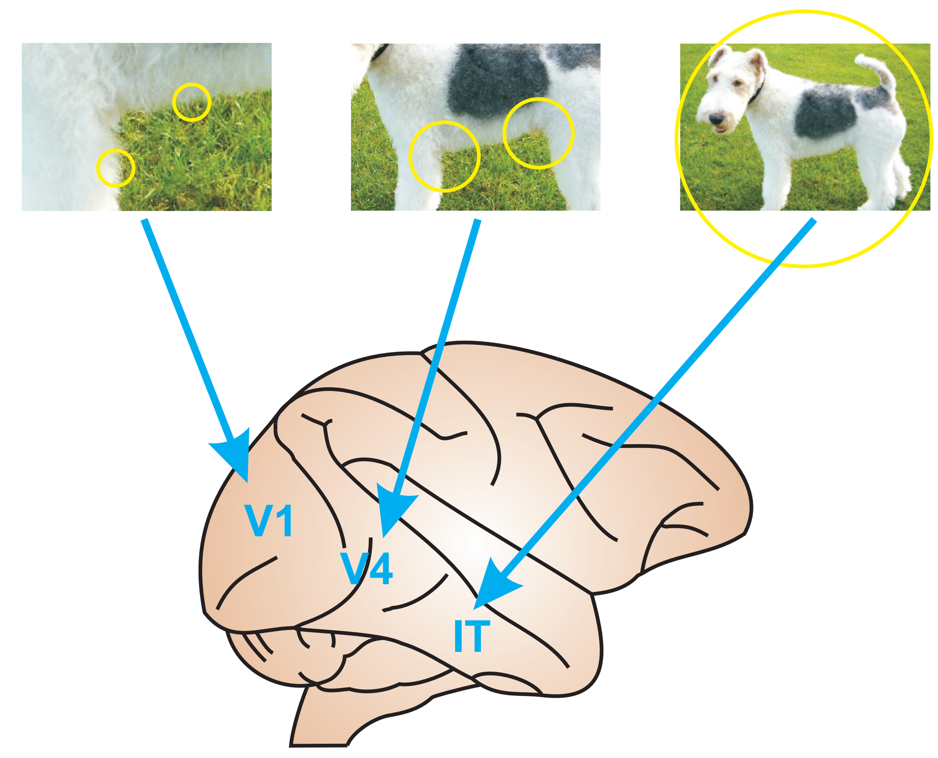
Introduction

Object/scene vision is arguably the most remarkable weakness in current machine intelligence. Extracting real-world information from natural visual images has proven to be an essentially insoluble computational problem. As a result, human observers are still required for determining what is in an image and what is happening in an image, and human controllers are still required to navigate intelligently through dynamic real-world environments. The huge gap between machine vision and biological vision makes this a prime target for mining computational algorithms from neural circuits.



Complexity of object/scene vision. Despite their variety and complexity, a human observer can easily recognize the content of these pictures. This is possible even without having encountered a particular scene or object before. Currently, no computer vision algorithm is able to solve this task.

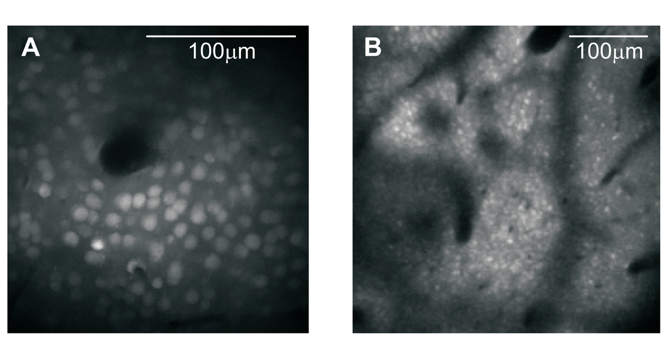
Neural algorithms of intermediate vision remain almost entirely unknown. Research on biological vision has focused on **(a)** pixel-level processing of orientation, color, and motion in primary visual cortex (V1), and **(b)** endstage signals for object identity and other semantic-level information in inferotemporal cortex (IT) and prefrontal cortex. The algorithms that transform (a) to (b) are implemented in intermediate cortical processing stages such as area V4. **Understanding these intermediate transformations is the only way to replicate biological vision in**



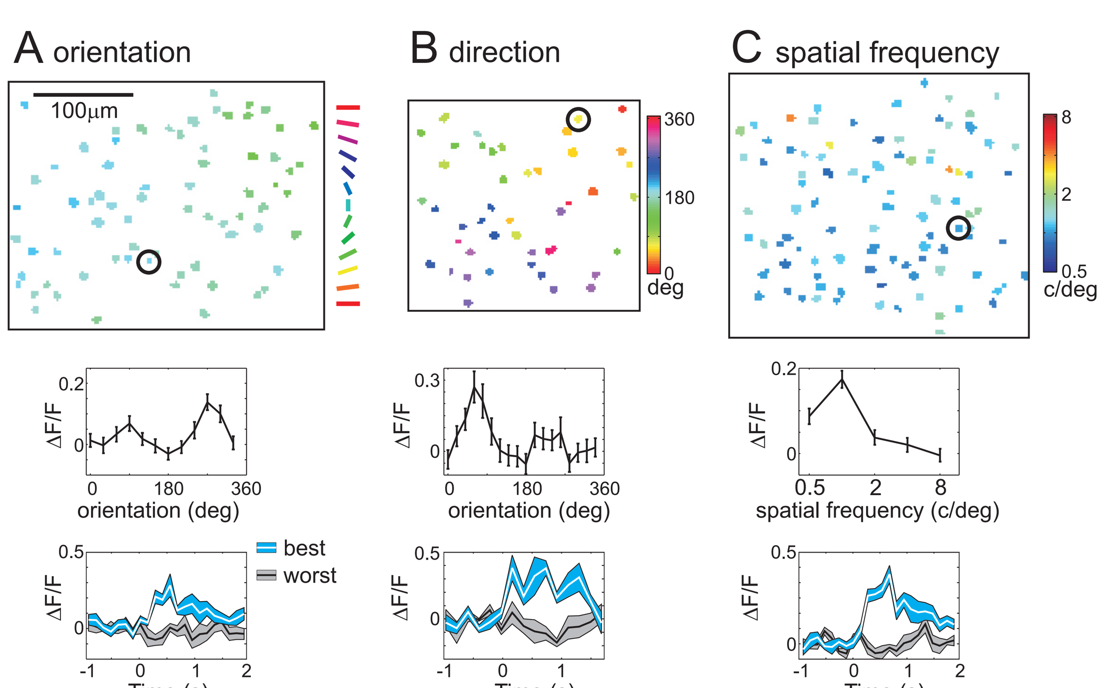
Transformation of visual information in the cortex. Along the visual pathway, increasingly more complex object information is encoded. While neurons in V1 respond to features of local edges, neurons in IT respond to entire objects. Intermediate areas such as V4 handle the important transformation between these stages. Neurons in V4 respond to complex parts of objects, encoding features such as contour curvature.

Approach

Two-photon microscopy: Our experiments use two-photon imaging of neural population activity to infer local circuit algorithms in area V4 of macaque monkeys, an animal model with extremely close functional and anatomical homology to human vision. Two-photon imaging far exceeds the sampling density achievable with other recording techniques. It allows us to observe signaling in 100s of densely packed, closely interacting neurons within a local cortical circuit. The basic processing module of the brain is the cortical column, a 0.5 mm diameter column of interconnected neurons. Two-photon imaging is the first technique for observing the information processing carried out by a cortical column.

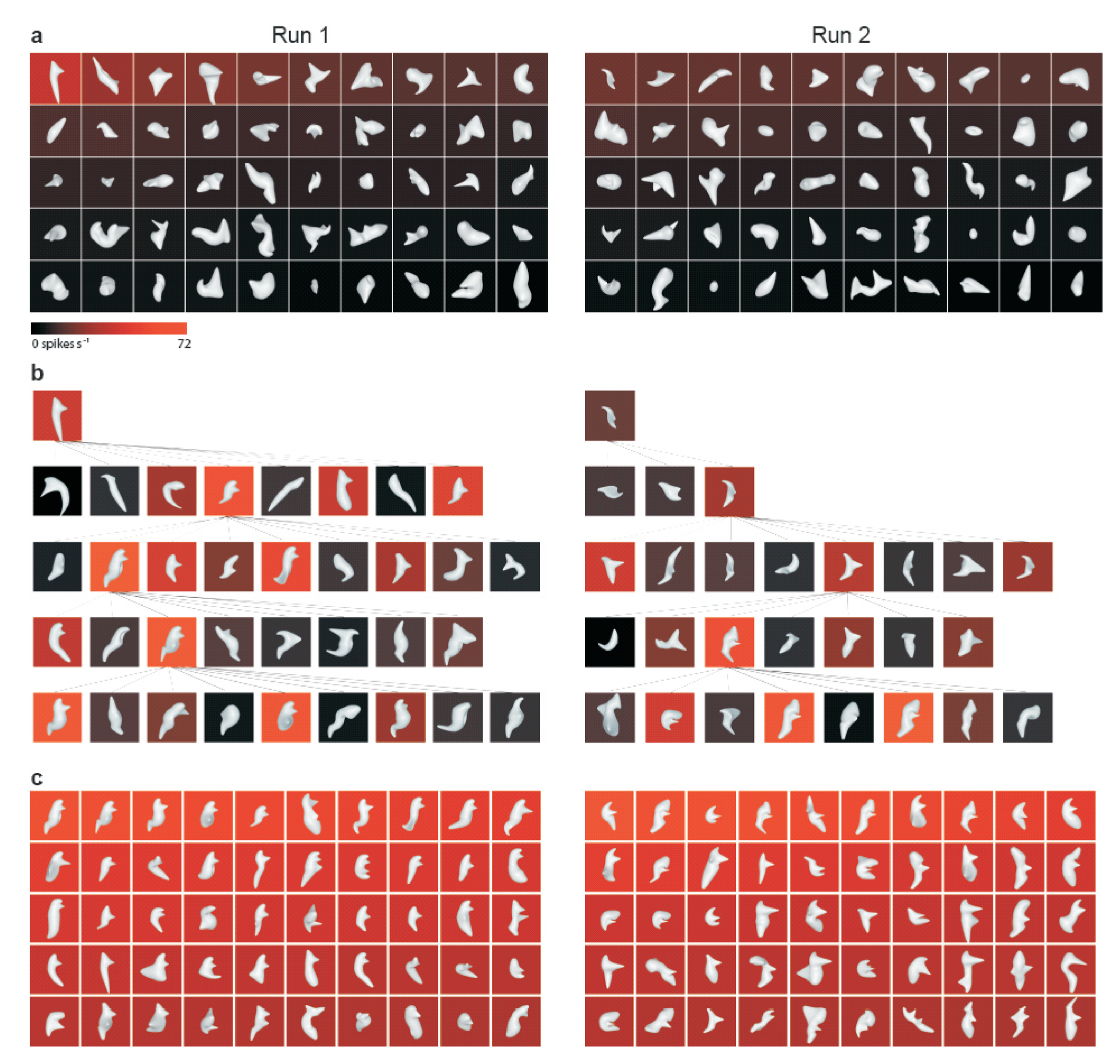


Two-photon imaging in monkey visual cortex. In these experiments, neurons are labeled with a fluorescent calcium indicator, Oregon Green BAPTA-1AM. The brain can be imaged with different resolutions, allowing access to neural algorithms operating on different spatial scales. (A) Example of fine scale imaging, showing a population of labeled neurons within 200 x 200 mm of cortex. (B) Example of large scale imaging.



Using two-photon imaging to determine the functional organization of V4 on the scale of cortical columns. (A) - (C) show the distribution of tuning properties across three V4 regions. In the images in the top row, every neuron is color-coded with its preferred stimulus parameter. The plots below show the tuning curve for an example neuron (highlighted with a circle), as well as the time course of responses to the best and worst stimulus. (A) Distribution of orientation preferences across a V4 region. (B) Distribution of direction preference. (C) Distribution of spatial frequency tuning.

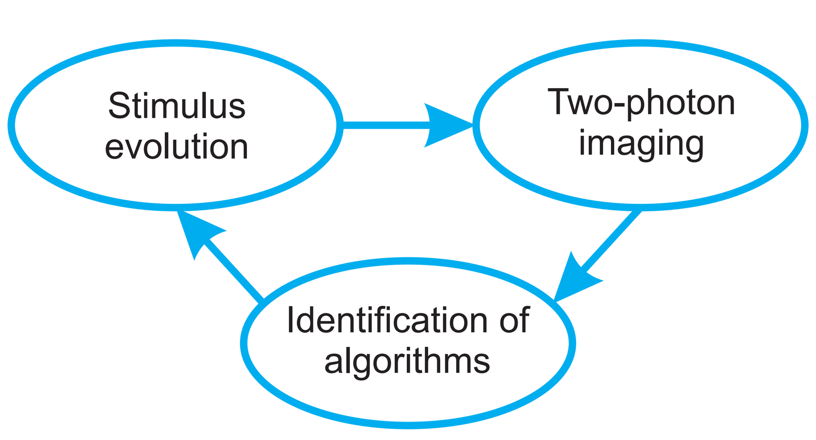
Evolutionary visual stimuli: Inferring algorithmic principles from two-photon data will require a new strategy for evoking a wide range of activity patterns in a V4 column. We would adapt our previous strategy of evolving visual stimuli guided by responses of individual neurons. Here, we would guide stimulus evolution with high-dimensional metrics for strength and variety of population activity patterns.



Evolving stimuli enable us to effectively drive responses in intermediate visual cortex. (a) Experiments start with randomly generated stimuli, only few of which drive neurons well. Response strength is indicated by the background color. Two independent stimulus lineages are indicated (run 1 and 2). (b) Stimuli are then evolved to build new stimulus generations. The figure shows the family tree for an example stimulus from each lineage. (c) Stimulus evolution enables to identification of additional stimuli that evoke strong neural responses.

Computational Development

We will recruit team members to develop and implement intermediate visual processing algorithms based on our neural circuit analyses. We envision an iterative process in which neural measurements inspire initial computational models, which can then be used to guide stimulus evolution and test more specific hypotheses about circuit functions, thus constraining models of increasing specificity and complexity.



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